Dynamic Fuzzy Logic Model for Risk Assessment of Marine Crude Oil Transportation

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ABSTRACT

As a scarce strategic resource, crude oil is closely intertwined with national strategies, global policies, international relationships and national competence. Unbalanced demand and production of crude oil leads to the huge amounts of import and export activities. Marine transportation accounts for about 80% of the total oil transport due to the low cost. However, marine transport incurs very high risk. Therefore, it is of great importance to assess and control risk effectively in crude oil transportation. In risk assessment, uncertainty evaluation becomes a key variable which cannot be neglected. Previous cases show that fuzzy logic can be used to manage uncertainty. However, using fuzzy logic usually encounters two difficulties, i.e. to determine the membership functions and to update the IF-THEN rules. This paper presents a dynamic fuzzy logic model (DFLM) which is able to meet the above-mentioned purposes. The DFLM is developed base on fuzzy theory and incident causation model. The model is examined using a hypothetical case. Preliminary results show that it reduce the time of risk assessment and increase the reliability of evaluation.

Keywords: Crude oil transportation, Risk assessment, Fuzzy logic, Safety
1. INTRODUCTION

Crude oil is one of the most important strategic resources all over the world. With the economic globalization and the complicated international situation, crude oil is playing and surely will play a vital role in the process of modern industry and modern civilization to any country and region. However, unbalanced demand and production of crude oil results in global trade movements, and those movements lead to large amount of import and export activities. According to International Energy Agency (IEA, 2009), global oil supply is 70.5 million barrels per day in 2008. For the oil production market, OPEC market share rate is more than 40%. It means that about 30 million barrels of crude oil is transported from Middle East to other countries every day, and crude oil transportation is of great importance.

Marine transport is the primary means of the crude oil transportation, which accounts for 80% of the total. As a high-risk mode of transport, different kinds of safety risks are existed during marine crude oil transportation, e.g., pirates, collisions between ships and other unforeseen accidents. The globalization of the shipping industry makes it difficult to establish safety incentive programmes which would lead to the reduction of the frequency of shipping accidents (Wilde, 1998). Some policies are adopted in specific areas to promote the safety, but they are not effectively reward ships with a lower ratio of accidents (Baniela, 2011). The total number of casualties, economic and environmental loss is keeping growing with global trade and the freight market (IUMI, 2010).

To improve the safety situation of marine transportation, especially for the crude oil transportation, one strategy would be to ensure continual improvement of safety management systems (SMS) of marine crude oil transportation. SMS is defined as an interdependent set of preventive measures, which is targeted at maintaining and improving safety performance of an organization (BSI, 1996). Figure 1 shows a basic risk management model, which is the foundation of SMS (BSI, 2000). The model consists of four elements: hazard identification, risk analysis, risk control selection, risk control implementation and maintenance. In this paper, the first three elements are mainly discussed, i.e., risk assessment and safety planning.

Risk assessments are often used to evaluate the safety of the marine oil transportation system, in order to find which additional safety measures can reduce the risk. It is better to use a linguistic value rather than crisp value, because uncertainty evaluation becomes a key variable. Fuzzy logic is an appropriate way to meet the conditions. Furthermore, it can output an OK message to help the decision.
maker to response quickly (Rainer, 2010). Nevertheless, since the linguistic value is determined by human senses, which will be affected by the times, human experiences and external factors. As a result, fuzzy logic can only be used in short-term safety assessment, and the cost is a huge amount of preliminary work. The method is not meet the needs of long-term safety management requirements, because of the redundancy and the lack of stability.

A dynamic fuzzy logic model (DFLM) is presented to improve the long-term safety management situation of marine crude oil transportation. The model can be divided into two parts, corresponding to the two important components of traditional fuzzy logic model. The first part of model updates the membership function. The key is to get a quantitative curve through the collection of historical statistics. The second part of model requires the retrieval of relevant safety knowledge from a safety knowledge base, using fault tree analysis (FTA) to establish and update a dynamic if-then rules database. This model is validated using a hypothetical case, in which the proposed methods are applied and tested.

2. LITERATURE REVIEW
The safety control in risk management was founded by Heinrich’s (1939) incident causation models, and numerous other models have been developed. The energy transfer models, as the name implies, focus on the transmission of uncontrolled energy from the source to the victim. The energy transfer model developed by Haddon (1980) has much relevance to this study. Haddon developed the model and proposed 10 basic prevention strategies based on the points of intervention. Hinze (1997) focused on psychological and behavioral aspects of humans. However, the models do not emphasize the role of the organization and the safety management system. Thus individual specific models do not facilitate continual improvement of SMS explicitly.

Bonvicini (1998) applied fuzzy logic to the risk assessment of the transport of hazardous materials by road and pipeline, and calculations are performed using fuzzy arithmetic. Douligeris (1998) established a marine oil transportation system model, which offered a framework of database mechanism. As limited of the IT technology, a large-scale simulation was unavailable at that time. Kowalewski (2010) analyzed the hazard to operator during design process of safe ship power plant, and found that the fuzzy logic based assessment is better compared with the classic matrix method. James (2008) combined combines both fuzzy logic and Decision Making Trial and Evaluation Laboratory (DEMATEL), and the method can map out the structural relations among diverse factors in a complex system and identify the key factors. Ronza (2007) did a Quantitative Risk Analysis (QRA) determining individual and societal risk on the basis of transportation accident databases.

3. APPLICATION of FUZZY LOGIC to RISK ASSESSMENT

3.1. Fuzzy Set
The basic concepts about fuzzy sets (George and Bo 1995) and their notation and terminology (Didier and Henri 1980) will be briefly introduced. A crisp set $A$ (that
is a classical non-fuzzy set) can be defined by a “membership function” \( \mu_A \), which can assume only the values 0 and 1: for each \( x \in X \), when \( \mu_A = 1 \), \( x \) is declared a member of \( A \), and when \( \mu_A = 0 \), \( x \) is as a non-member of \( A \).

However, concepts very often contain some vagueness that does not allow dividing elements in such a sharp way between two groups in the natural language, members and non-members. This vagueness could mathematically be represented by allowing the characteristic function to assume all values between 0 and 1, so expressing different grades of membership of each element \( x \in X \) in \( A \).

Apart from the membership function, a fuzzy set can also be fully and uniquely represented by its \( \alpha \)-cuts. Given a fuzzy set defined on \( X \), an \( \alpha \)-cut is the crisp set that contains all the elements of \( X \) whose membership grades in \( A \) are greater than or equal to the specified value of \( \alpha \).

Fuzzy arithmetic consists of performing arithmetic operations on fuzzy numbers in terms of arithmetic operations on their \( \alpha \)-cuts, i.e. on closed intervals, using the rules and the notations of an area of classical mathematics called "interval analysis". Basically, the endpoints of the \( \alpha \)-cuts, on which the operation has to be performed, must be combined according to the operation. The minimum and maximum values of the solution will define the lower and upper endpoints of the solution interval, respectively.

### 3.2. Fuzzy Numbers and Fuzzy Arithmetic

If a fuzzy set \( A \) defined on the set of all real numbers \( R \) has the following three properties: (1) \( A \) is a fuzzy set whose largest membership grade is 1, (2) the \( \alpha \)-cuts of \( A \) for every \( \alpha \in (0, 1] \) are closed single intervals, and (3) the strong \( \alpha \)-cut for \( \alpha = 0 \) is bounded; it is called a “fuzzy number”.

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Figure 2 shows the usage of fuzzy sets in the field of risk assessment. In detail, a crisp value of 8 is translated into a fuzzy set using the membership function. As a result the set belongs with a factor of 0.25 to "Medium" and with a factor of 0.5 to "High".
3.3. An Application of Fuzzy Logic

The characteristic of fuzzy logic is very suitable for risk management. Fuzzy set theory can be helpful in dealing with the vagueness of human thought and expression in decision making. In particular, linguistic ambiguities can be represented through the conversion of linguistic variables into fuzzy numbers (Wu and Lee, 2007). Fuzzy numbers expand on the idea of the confidence interval and are defined over a fuzzy subset of real numbers.

A linguistic variable is one whose values are words or sentences in natural or artificial language. Its use is a convenient way for decision makers to express their assessments (Malaviya and Peters, 1997). Table 1 and Figure 3 offer a simple example of the use of fuzzy logic.

**TABLE 1 The if-then rules of fuzzy logic**

<table>
<thead>
<tr>
<th>Weather</th>
<th>Pirates</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Fine</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Fine</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>General</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>General</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>General</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Bad</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Bad</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Bad</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
When a tanker into an area, someone (maybe a safety supervisor) is supposed to score the weather and pirates condition (out of 10). It is assumed that the score of weather is 3, and the score of pirates is 8. As the rules illustrated in Figure 3, the output is 6.39, which represents the risk level is medium.

4. DYNAMIC FUZZY LOGIC MODEL

4.1. The Advantage of the Model
The application of fuzzy logic is appropriate for risk assessment. However, traditional fuzzy logic is short-term, and it is not suitable for a long-term safety monitoring. Dynamic fuzzy logic model (DFLM), which is stable, flexible and sustainable, can meet the needs of the current situation.

DFLM can build a framework of risk assessment. In marine crude oil transportation, it can offer experience to expert, thus the adjustment of fuzzy logic is available. The effect of DFLM is to update the membership function and the IF-THEN rules, and a fuzzy logic database is also needed.

4.2. Update of Memberships Function
The linguistic value changes in different period. For example, the total loss rate of ship continuously decreased with the development of technology and management (Qin T.R, 2005). In 1960s, people regarded 5-7‰ as the average level of total loss rate of ship. In 1990s, 2-4‰ is the average level. Expressed by linguistic value, 6‰ was "Medium" in 1960, but it probably became "High" in 1980. In table 2, the trend of total loss rate of ship is summarized.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total loss rate(‰)</th>
<th>Linguistic Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948-1979</td>
<td>5-7</td>
<td>Medium</td>
</tr>
<tr>
<td>1980-1999</td>
<td>2-4</td>
<td>Medium</td>
</tr>
<tr>
<td>2000-2005</td>
<td>less than 2</td>
<td>Medium</td>
</tr>
</tbody>
</table>

As a result, an update of membership function is necessary.
4.3 Update of IF-THEN Rules

IF-THEN Rules is another important aspect of fuzzy logic. There are many new hazards, which impact the safety of crude oil transportation, appear with the progress of the age, e.g. terrorism. On the contrary, some hazards can be neglect with the development of technology.

Figure 4 shows feedback mechanisms to rules. A new factor can be found by incident investigation, thus the experts can summary the experience and update new rules.

4.4 Fuzzy Logic Database

Constructing a fuzzy logic database is helpful to the application of DFLM. Extending Douligeris's(1998) oil spill and transportation database, the fuzzy logic database is established.
The database can store information about the accident of marine oil transportation. Table 3 shows the framework of database. Hazard name is got by the feedback mechanisms. Hazard importance can ordinate the hazard names, and it is helpful to establish the rules. Hazard frequency can determine the membership function.

**TABLE 3 The framework of fuzzy logic database**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Class</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard Name</td>
<td>Char</td>
<td>Mem. Fun. &amp; Rules</td>
</tr>
<tr>
<td>Hazard Importance</td>
<td>Int</td>
<td>Rules</td>
</tr>
<tr>
<td>Hazard Frequency</td>
<td>Double</td>
<td>Mem. Fun.</td>
</tr>
</tbody>
</table>

Table 4 and Table 5 show the relationship between the reality probability and the linguistic value.

**TABLE 4 The definition of linguistic value on the basis of accident probability**

<table>
<thead>
<tr>
<th>Level</th>
<th>Linguistic value</th>
<th>Accident probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,0.1,0.2</td>
<td>few</td>
<td>&lt;1</td>
</tr>
<tr>
<td>0.3,0.4,0.5</td>
<td>less</td>
<td>10—100</td>
</tr>
<tr>
<td>0.6,0.7,0.8</td>
<td>general</td>
<td>100—1000</td>
</tr>
<tr>
<td>0.9,1.0</td>
<td>frequent</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>
TABLE 5 The definition of linguistic value of time

<table>
<thead>
<tr>
<th>Level</th>
<th>Personnel losses</th>
<th>Economic Loss</th>
<th>Environmental Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.1,0.2</td>
<td>light</td>
<td>none</td>
<td>low</td>
</tr>
<tr>
<td>0.3-0.4,0.5</td>
<td>Critical</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>0.6-0.7,0.8</td>
<td>fatal</td>
<td>Serious injured</td>
<td>serious</td>
</tr>
<tr>
<td>0.9,1.0</td>
<td>Disaster</td>
<td>death</td>
<td>very serious</td>
</tr>
</tbody>
</table>

5 CONCLUSION

This paper presents a dynamic fuzzy logic model, which may help to increase the security of marine crude oil transportation. The output of risk assessment is usually expressed by linguistic value such as 'high' and 'low'. Instead of crisp values, dealing with qualitative linguistic terms which are computed by a fuzzy algorithm is more advantageous. Compared with the traditional fuzzy model, the DFLM is designed to provide a systematic and logic structure for long-term safety management.

The effect of DFLM offers two update mechanisms of fuzzy logic. Through the use of the DFLM as a common model for updating membership function and IF-THEN rules, membership function's updating information can be retrieved and utilized in IF-THEN rules' updating. However, in order to fully exploit the ideas and concepts of DFLM, a database system meant to assist update membership function and IF-THEN rules will be necessary. Hence an intelligent database system will be developed to implement the DFLM approach. With the database system, the efficiency and the robustness of risk assessment can also be improved, allowing the rapidly changing transportation environment to deal with safety issues more effectively and efficiently.

REFERENCES


